

ESTIMATES OF MEAN MAXIMUM MIXING DEPTHS IN THE CONTIGUOUS UNITED STATES

GEORGE C. HOLZWORTH

U.S. Weather Bureau Research Station,¹ Cincinnati, Ohio

ABSTRACT

Mean radiosonde observations and normal maximum surface temperatures are used with the assumption of a dry adiabatic lapse rate to estimate monthly mean maximum mixing depths (MMD's) for 45 stations in the contiguous United States. From these data isopleth analyses of mean MMD's are presented for each month. Deviation from the assumption of a dry adiabatic lapse rate is discussed. Sixteen of the available 45 radiosonde stations are selected as generally representative of the United States and are subjected to further considerations. These considerations are (1) the relationship between monthly mean MMD's computed from mean observations and from individual observations, (2) comparison of monthly mean MMD's based on observations for 1 year with those based on observations for 10 years, and (3) the standard deviations of daily MMD's.

1. INTRODUCTION

Community air pollution may be defined to occur when the concentrations of pollutants reach objectionable levels over a significant portion of a community. Such concentrations are attained when the atmosphere is unable adequately to dilute community pollutants. In this report attention is directed toward atmospheric dilution in the vertical dimension over the horizontal scale of a community; the conclusions are not necessarily applicable to considerations of close-in diffusion from a point source.

The layer of air adjacent to the ground (ranging from a few hundred to perhaps a few thousand meters) typically displays considerable diurnal variation in its temperature structure and the depth through which pronounced mixing occurs. Except for limited tower information and limited military radiosonde observations, vertical temperature profile data are available only at 12-hr. intervals at U.S. Weather Bureau radiosonde stations. Consequently it is necessary to infer diurnal variations in vertical mixing depths from these "spot" observations.

From radiosonde observations at four different times of day² Hosler [1] studied the frequency of inversions and/or isothermal layers based within 500 ft. of the surface for the contiguous United States. He estimated that these extreme conditions of implied limited vertical mixing may be expected during more than one-fourth of all possible hours in all seasons over almost the entire United States. During fall and winter the low-level inversions may be expected during more than half of all possible hours over large portions of the western United States.

Hosler also considered the highest frequency of low-level stability conditions that occurred at any one of the four observation times. His tabulations showed that inver-

sions and/or isothermal layers within 500 ft. of the surface occurred during more than half of all observations at a particular time (usually at night) in all seasons over almost the entire United States. Over the western mountains these conditions often occurred in more than nine-tenths of the observations at a particular time. Hosler's tabulations showed that the frequencies of stable conditions observed during darkness, or very shortly thereafter, were usually much greater than those observed at other times. Thus, as Hosler indicates, marked stability at very low levels is generally the rule at night; that is, vertical mixing is frequently minimal at night. For the consideration of air pollution episodes that persist through a day it is important to know the extent of vertical mixing during daytime when such mixing is typically maximal. The purpose of this study, as a supplement to Hosler's work, is to provide estimates of maximum mixing depths (MMD's) for the contiguous United States.

It should be mentioned again that only the extent of vertical mixing is being considered in this study. This emphasis is not intended to detract in any way from the importance of horizontal mixing in atmospheric dispersion. It is the *simultaneous* occurrence of limited horizontal and vertical mixing that is commonly observed preceding and during high levels of community air pollution. However, the desired information about such occurrences is not readily determinable, making it necessary to treat the matter less directly. The estimates to be presented are for the diurnal time when the extent of vertical mixing is typically greatest. They are not overall indices of a climatological potential for community air pollution. They may be used for that purpose only when properly combined with other pertinent information, which might include mixing depths during other parts of the diurnal cycle and relevant wind data. The treatment and extent

¹ Robert A. Taft Sanitary Engineering Center, Division of Air Pollution, Public Health Service, U.S. Department of Health, Education, and Welfare.

² Two observations per day but extending over a period during which the standard observation times differed by 3 hr.

of such other pertinent information should be dictated by the purpose, scope, and desired detail of the index.

2. PROCEDURE

In order to estimate MMD's it is necessary to make some general assumptions, based upon meteorological experience, about the manner in which the vertical temperature structure of the lower atmosphere varies diurnally. Briefly, these are that nocturnal radiational cooling of the ground and heat loss from the air to the cool ground result in stable lapse rates at night; and that during daytime, absorption of solar radiation by the ground and heat conduction to the air in contact with the warm ground result in unstable lapse rates and vertical motions (mixing) that ultimately produce a mixed dry adiabatic layer. Neglecting as insignificant other factors (advection, subsidence, etc.) that could cause changes in the vertical temperature profile between its time of observation and that of the surface maximum temperature, it is assumed that the MMD depends upon the vertical temperature structure and the surface maximum temperature. This last assumption must be further conditioned by the fact that effects of vertical wind shear and mechanical turbulence in augmenting or diminishing vertical mixing have been neglected. In some cases these factors may be important, but here only the effects of convection are considered. Since radiosonde observations are seldom made at the times of maximum surface temperatures, MMD's were estimated by extending a dry adiabat from the maximum surface temperature to its intersection with the most recently observed temperature profile. It should be recognized that the computed MMD's represent the mean maximum depth of *vigorous* vertical mixing due to convection. Some penetrative convection is usually expected, but is more likely to be important in those cases where the MMD is topped by a conditional lapse rate than by a more stable lapse rate. The extreme of the latter case would be a temperature inversion in which little or no penetrative convection would be expected. Such effects will be mentioned only briefly in this report. Finally, it should be realized that the estimated *mean* MMD's are comprised of daily MMD's that extend over a wide range at most locations.

From the above discussion of assumptions and conditions, which have not been completely exhausted, it is clear that the computed MMD's are approximations. They are, however, thought to be reasonable estimates suitable for practical applications.

The computation of the daily MMD's for 45 radiosonde stations in the contiguous United States for several years is a formidable task. In order to reduce this work, monthly averages of 0300 GMT radiosonde observations during 1946–1955 (Ratner [2]) and corresponding normal maximum surface temperatures during 1921–1950 were utilized to estimate mean MMD's for each month. This procedure raises a question about the relationship of (a) mean MMD's computed from average temperature pro-

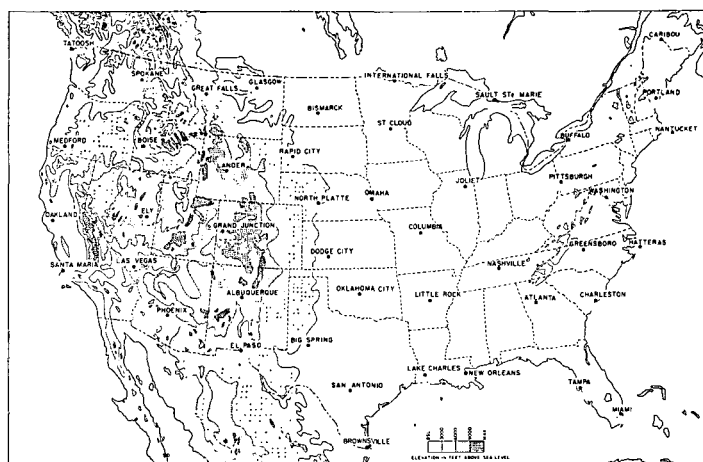


FIGURE 1.—Stations for which 10-yr. average radiosonde data are available from Ratner [2], and for which monthly mean maximum mixing depths were computed.

files and normal maximum surface temperatures to (b) mean MMD's computed from daily temperature profiles and daily maximum surface temperatures. This relationship, which was found to be surprisingly good, will be discussed in section 4.

3. MEAN MAXIMUM MIXING DEPTHS

The 45 stations for which monthly mean MMD's were estimated from average temperature profiles and normal maximum surface temperatures are shown in figure 1. Based upon these estimates, isopleths of MMD above the surface were analyzed for the contiguous United States. As an aid to the analyses close attention was paid to topography. Also considered were monthly average daily maximum temperature isotherms and isolines of average daily temperature range in the United States (as given periodically on the back of the *Daily Weather Map* [3]), and mean sea surface isotherms near the coasts. The MMD isopleths are shown for each month in figures 2–13 (January–December, respectively). The MMD estimates for each station, which are also given in table 1, are shown in meters above the surface and the isopleths are labeled in hundreds of meters above the surface.

As shown by figures 2–13, the mean MMD's are generally least in December and January when they are mostly 200–800 m. and are greatest during May through August when they exceed 3000 m. over parts of the Rockies and exceed 1600 m. over parts of the Appalachian region of the East. At most inland stations mean MMD's increase markedly during February, March, and April and decrease rapidly in September, October, and November. Along the Pacific and Atlantic coasts, and to a lesser extent along the Gulf coast and in the Great Lakes area, mean MMD's show only relatively slight variations throughout the year.

Along the Pacific and Atlantic coasts mean MMD's are particularly shallow throughout most of the year. This feature is attributed at least in part to the cool coastal

TABLE 1.—Computed monthly mean maximum mixing depths (meters above surface)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Albuquerque, N. Mex.	710	1370	2380	2700	3650	3520	3400	3100	1920	1330	1020	620
Atlanta, Ga.	360	620	930	1280	1480	1680	1640	1560	1400	910	680	470
Big Spring, Tex.	630	910	1210	1390	1630	2010	2290	2480	1610	1120	900	500
Bismarck, N. Dak.	410	350	860	1100	1600	1540	1720	1360	1140	740	440	180
Boise, Idaho.	310	440	1600	1630	2170	2360	2280	1700	630	750	480	230
Brownsville, Tex.	640	830	800	880	970	1210	1280	1370	1240	1200	890	590
Buffalo, N. Y.	480	530	780	810	1070	1180	1440	1360	1190	530	700	510
Caribou, Maine.	350	300	550	660	1090	1030	980	930	790	380	320	220
Charleston, S.C.	550	730	980	1190	1350	1330	1200	1060	1150	980	790	690
Columbia, Mo.	440	500	960	990	1090	830	1310	1140	880	730	680	400
Dodge City, Kans.	430	540	1020	1120	1350	1400	1820	1710	1180	790	660	360
El Paso, Tex.	760	1310	1800	2080	3100	3020	2740	2400	1780	1220	1040	580
Ely, Nev.	760	1130	2200	2610	3420	3830	3980	3780	2610	1830	1340	840
Glasgow, Mont.	280	230	830	1210	2100	2070	2280	1620	1110	670	200	180
Grand Junction, Colo.	340	670	1870	2530	3380	3570	3210	2970	2370	1090	770	430
Great Falls, Mont.	660	520	1480	2050	2470	2550	2800	2350	1570	1180	720	440
Greensboro, N.C.	390	650	1130	1180	1530	1790	1490	1420	1370	1020	840	580
Hatteras, N.C.	280	330	500	490	570	790	700	730	780	590	500	430
International Falls, Minn.	440	490	820	980	1520	1490	1390	1140	1020	530	450	420
Joliet, Ill.	480	480	980	950	1040	1090	1380	1310	860	790	600	480
Lake Charles, La.	520	740	870	1050	1130	1280	1300	1250	1320	1200	840	590
Lander, Wyo.	170	300	1240	1350	2530	2610	2730	2290	1410	630	300	190
Las Vegas, Nev.	620	1600	1680	2310	2950	3760	3790	3650	2490	1170	780	610
Little Rock, Ark.	460	630	950	1060	1130	1260	1490	1450	1240	970	710	530
Medford, Oreg.	400	1050	1900	1840	2120	2300	2180	2360	1550	1050	420	310
Miami, Fla.	1240	1430	1300	1560	1540	1480	1570	1460	1380	1320	1180	1190
Nantucket, Mass.	360	330	470	340	350	360	350	430	440	250	350	490
Nashville, Tenn.	520	670	1050	1320	1470	1550	1630	1560	1500	1120	900	630
New Orleans, La.	390	680	830	1040	1040	1290	1320	1180	1140	960	680	500
North Platte, Nebr.	470	580	1120	1280	1660	1340	1640	1450	1020	950	770	460
Oakland, Calif.	550	690	1100	790	690	660	430	470	470	570	490	480
Oklahoma City, Okla.	430	570	960	1050	1160	1160	1590	1530	1110	790	680	430
Omaha, Nebr.	370	370	900	1070	1360	1130	1340	1060	850	670	500	330
Phoenix, Ariz.	940	1160	2090	2200	3040	2870	2760	2170	1180	1020	1080	760
Pittsburgh, Pa.	340	590	1040	1150	1510	1370	1450	1370	1240	630	730	410
Portland, Maine.	430	480	730	780	740	820	810	870	780	500	530	430
Rapid City, S. Dak.	400	460	1000	1230	1670	1390	1550	1510	1240	900	740	410
St. Cloud, Minn.	400	370	740	950	1340	1260	1400	1170	990	600	480	350
San Antonio, Tex.	500	790	1020	1160	1270	1530	1830	1930	1480	1200	830	560
Santa Maria, Calif.	860	810	1160	820	730	650	460	510	500	650	820	840
Sault Ste. Marie, Mich.	340	340	510	600	800	730	900	840	730	350	400	340
Spokane, Wash.	240	250	1070	1400	1580	1970	2290	2030	1060	760	250	190
Tampa, Fla.	730	950	940	1310	1410	1360	1310	1290	1270	1290	1000	810
Tatoosh, Wash.	600	510	740	740	420	350	280	230	150	280	230	420
Washington, D.C.	400	570	1000	930	1120	1310	1180	990	980	570	680	480

waters of these areas. Especially during the warmer months, large gradients of MMD occur along the Pacific and Atlantic coasts. These gradients, which are largely dependent upon the extension inland of cool sea breezes and topographical features, should probably be stronger than shown in some coastal regions. In the West the MMD gradients are so large that on figures 6-10 it was necessary for clarity to draw the isopleths in intervals of 400 m. rather than the usual 200-m. interval. It should be noticed that large gradients of MMD are also common over the Rockies, especially during the warm months.

During summer in the Great Lakes region mean MMD's are relatively shallow because maximum temperatures over the water are less than over the adjacent land. During winter the Lakes are partially frozen over and the unfrozen parts may have temperatures that exceed the maximum temperatures over nearby land. With such conditions MMD's would be greater over the unfrozen parts of the Lakes than over the adjacent land. This is usually assumed to be the case when cold outbreaks and evaporation from the Lakes result in snow showers downwind. However, without information about the mean ice conditions and surface water temperatures over the Great Lakes, the behavior of MMD's there during winter is difficult to determine.

From April through October a trough of shallow MMD's extends southwestward into the Central States from the Great Lakes region. This pattern appears to be a consequence of the deeper MMD's that are centered over the

higher terrain to the east and west during the warmer part of the year.

4. FURTHER CONSIDERATIONS

The computation of mean MMD's from average temperature profiles and normal maximum surface temperatures raises a question of the relationship of such computations to the mean of daily MMD's computed from individual observations. In this respect it should be pointed out that the available mean temperature profiles [2] were obtained by averaging the radiosonde observations at the surface, 1000 mb., and each succeeding 50 mb. (about 450 m.) above. Thus, the mean temperature profiles are less detailed than the individual profiles, which are specified wherever the lapse rate changes significantly. These differences in profile detail could result in differences between mean MMD's based on averaged observations and those based on individual observations. The correspondence between mean MMD's computed from mean and individual observations was studied by considering the 0300 GMT radiosonde observations for January and July 1956 and corresponding maximum surface temperatures for 16 of the 45 stations used in the isopleth analyses. These 16 stations were selected as representative of various sections of the United States.

In table 2, column II gives the average MMD's as computed from average temperature profiles (surface, 1000 mb., 950 mb., etc.) and average maximum surface

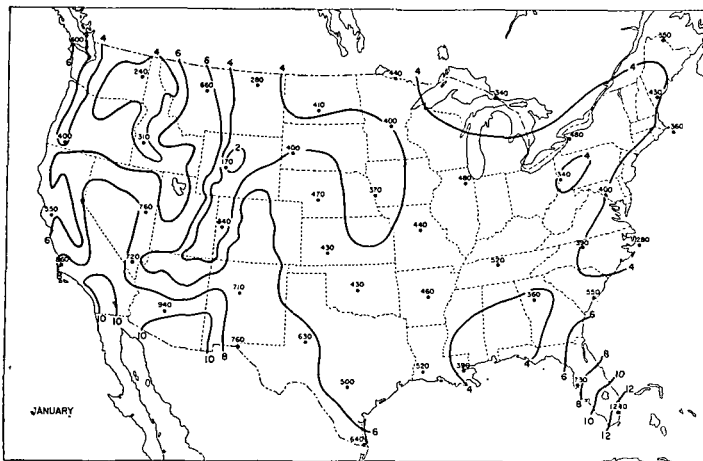


FIGURE 2.—Mean maximum mixing depths in meters above the surface during January. Isopleths are labeled in hundreds of meters.

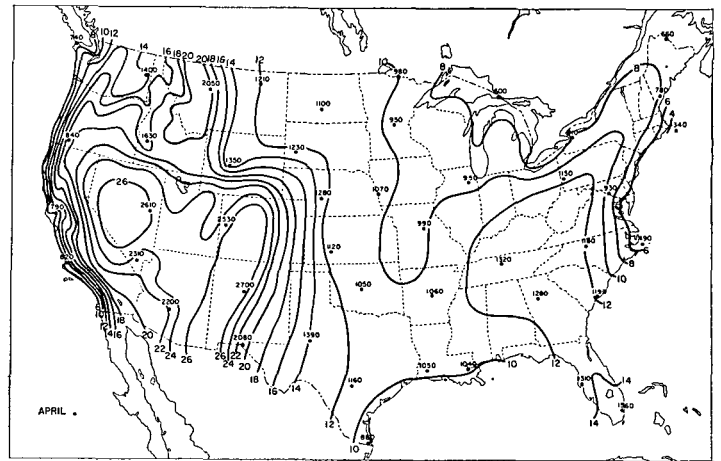


FIGURE 5.—Mean maximum mixing depths, April.

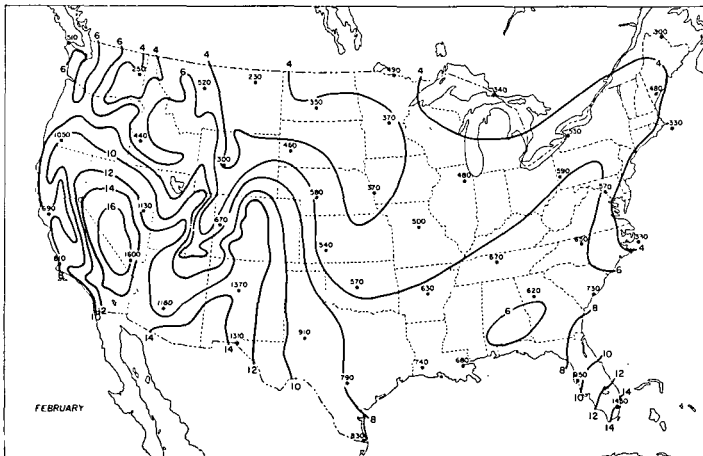


FIGURE 3.—Mean maximum mixing depths, February.

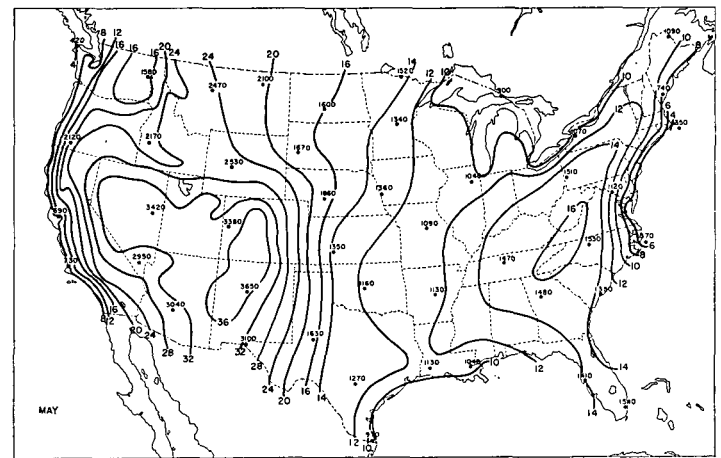


FIGURE 6.—Mean maximum mixing depths, May. Notice that over the western portion of the United States isopleths are in 400-m. intervals instead of the usual 200-m. intervals.

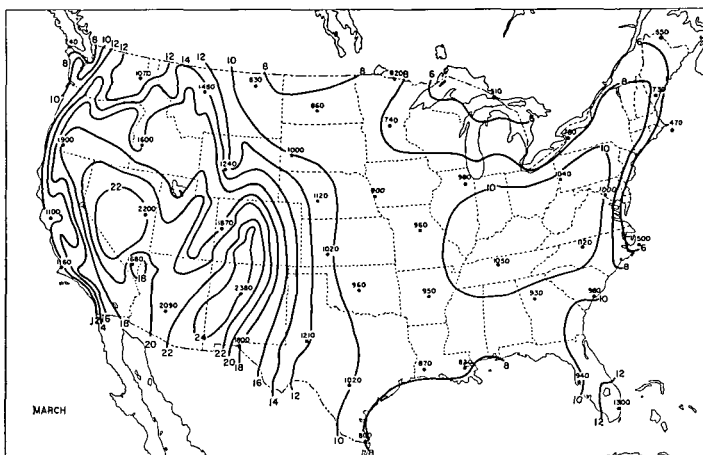


FIGURE 4.—Mean maximum mixing depths, March.

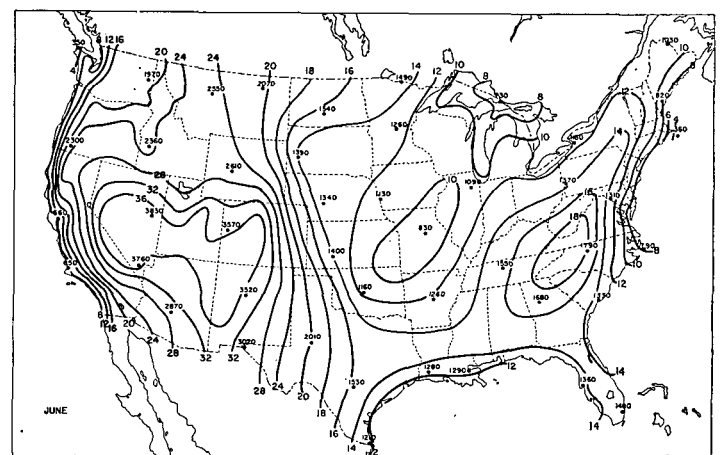


FIGURE 7.—Mean maximum mixing depths, June.

temperatures for January and July 1956. These values may be compared with those in column III, which give the averages of each daily MMD for January and July 1956. In the computation of these daily MMD's all

points of each radiosonde observation were utilized together with the corresponding daily maximum surface temperature. At most stations the average MMD's based on individual daily observations are somewhat

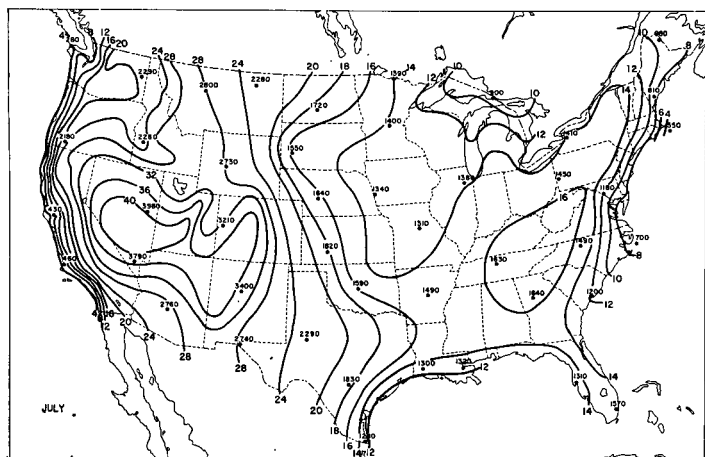


FIGURE 8.—Mean maximum mixing depths, July.

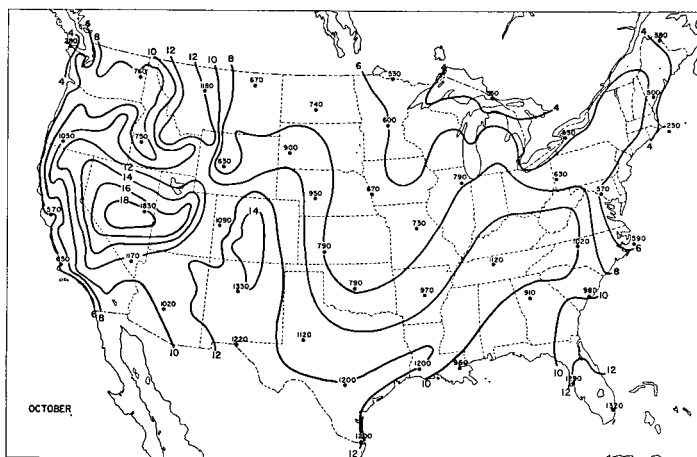


FIGURE 11.—Mean maximum mixing depths, October.

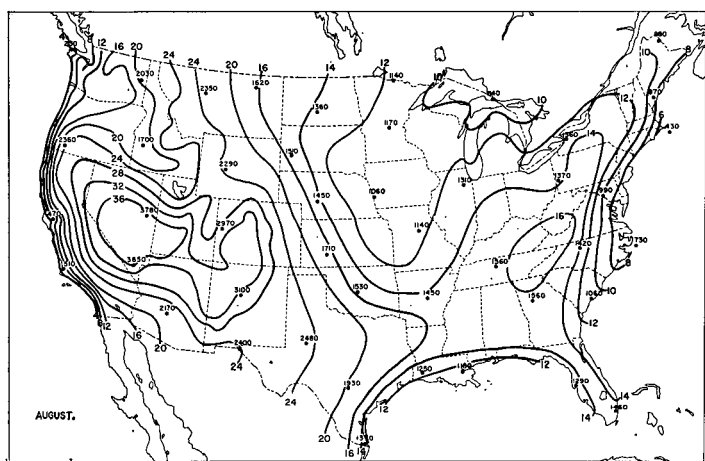


FIGURE 9.—Mean maximum mixing depths, August.

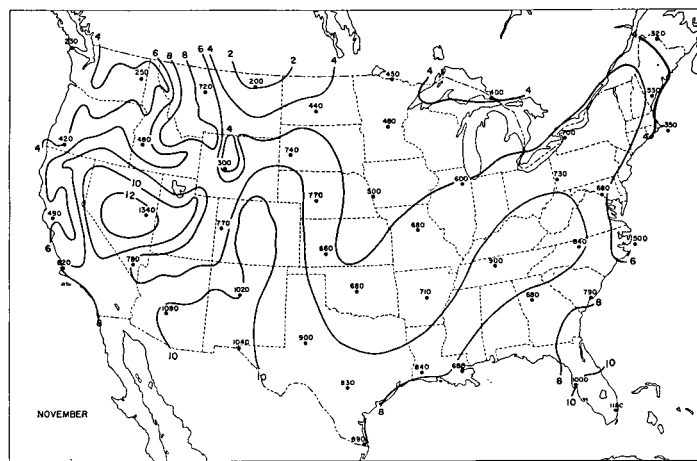


FIGURE 12.—Mean maximum mixing depths, November.

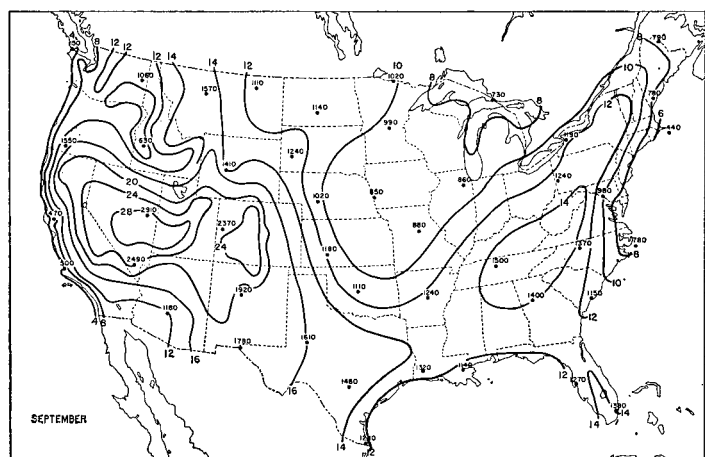


FIGURE 10.—Mean maximum mixing depths, September.

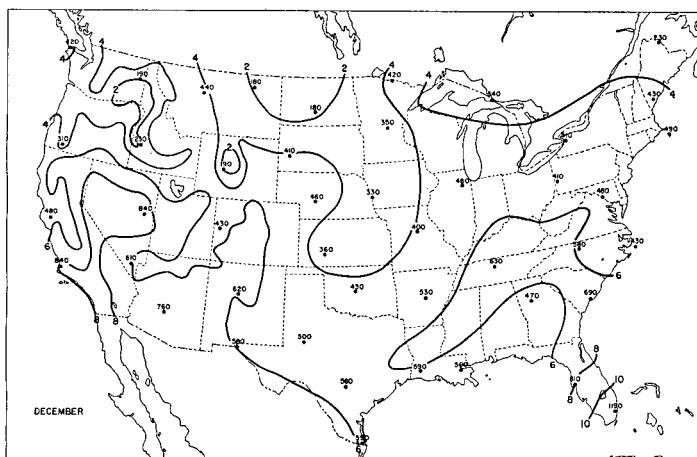


FIGURE 13.—Mean maximum mixing depths, December.

greater than those based on mean observations. This is especially true in January when for the 16 stations in table 2, the average MMD based on individual observations is 106 m. greater than that based on average observations. In July this average difference is 57 m.

The correspondence between average MMD's computed from mean and individual observations, as given in table 2, may be seen more clearly by referring to figure 14 (January) and figure 15 (July) where they are plotted one against the other, and for which least squares regression

TABLE 2.—Computed maximum mixing depth (meters)

	January					July				
	Avg. Obs. for		Daily Obs. for 1956			Avg. Obs. for		Daily Obs. for 1956		
	10 & 30 yr.*	1956	Avg.	St. Dev.	Range	10 & 30 yr.*	1956	Avg.	St. Dev.	Range
	(I)	(II)	(III)	(IV)	(V)	(I)	(II)	(III)	(IV)	(V)
Brownsville.....	640	830	910	320	170-1750	1280	1100	1080	230	320-1550
Caribou.....	350	370	380	320	0-1310	980	1310	1400	640	60-2920
Ely.....	760	880	1140	800	40-4020	3980	3830	3820	740	2450-5190
Great Falls.....	660	270	440	500	30-2000	2800	2240	2300	830	630-2480
Hatteras.....	280	280	330	400	0-1470	700	670	660	280	170-1400
International Falls.....	440	340	390	280	20-1240	1390	1330	1320	620	60-2330
Lander.....	170	230	570	680	50-2840	2730	3540	3640	1030	1600-5520
Miami.....	1240	1100	1190	430	60-2130	1570	1460	1450	230	1000-2100
Nashville.....	520	650	740	530	90-2590	1630	1940	1940	530	520-2910
Oakland.....	550	340	470	390	40-1710	430	400	500	140	280-930
Oklahoma City.....	430	410	440	290	90-1270	1590	1410	1400	720	340-3100
Omaha.....	370	380	420	330	70-1870	1340	1420	1650	670	640-3100
Phoenix.....	940	430	620	410	80-1910	2760	890	970	610	80-2410
Pittsburgh.....	340	630	600	470	0-2220	1450	1080	1200	440	260-2440
Santa Maria.....	850	560	640	330	210-1400	460	450	510	120	320-820
Tatoosh.....	600	380	490	430	50-2000	280	190	330	220	30-860

*10-yr. average radiosonde data and 30-yr. normal maximum surface temperatures.

lines have been fitted. In January and July the coefficient of correlation is 0.862 and 0.997, respectively. In July the slope of the regression line is practically 1.0 and the *Y*-intercept is relatively small, indicating very nearly a one-to-one correspondence between MMD's based on average and individual observations. In January the regression line slope is 0.885, not greatly different from 1.0, and the *Y*-intercept is relatively small, indicating a fairly close approximation to a one-to-one correspondence. The relationships discussed above for January and July are considered representative of winter and summer. Similar relationships are expected to hold for spring and fall. It is concluded that average MMD's computed from average observations slightly underestimate the average MMD's computed from individual observations. This effect is most pronounced in winter. However, in view of the approximate nature of the computations and the general purpose for which they are intended these differences are not considered significant.

Included in table 2 are mean MMD's based on mean observations over 10 and 30 yr., column I, which may be compared to those for 1956, column II. In most cases the single year (1956) averages are in fair agreement with the long-term means, but at some stations the two differ appreciably. At Phoenix in January the long-term mean MMD was 940 m. while for 1956 it was only 430 m. This difference is attributed mainly to the fact that in the first 1500 m. above the surface the mean temperature profile for January 1956 was 4°C. higher than the long-term mean temperature profile, and the average maximum surface temperature for January 1956 was only about 2°C. above normal. Clearly, such circumstances lead to a lower average MMD. At Phoenix in July the long-term mean MMD was 2760 m., while for 1956 it was only 890 m. This difference is attributed primarily to the fact that the

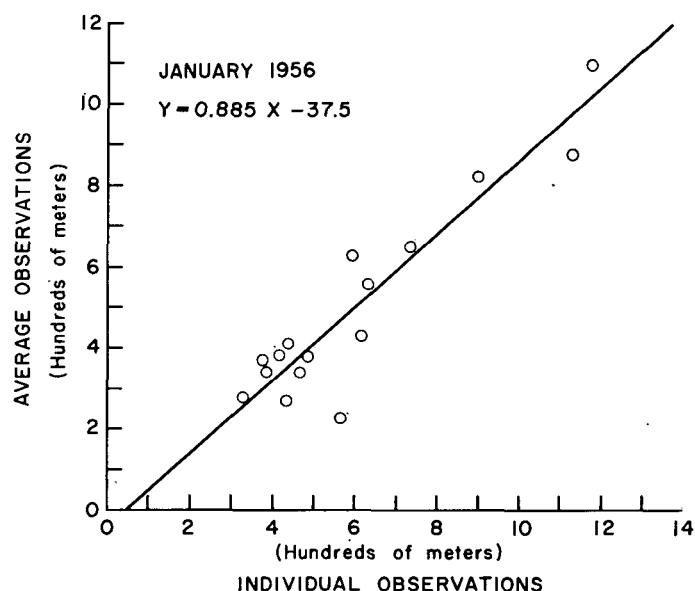


FIGURE 14.—Average maximum mixing depths during January 1956, computed from individual daily observations and from monthly average observations.

average maximum surface temperature in July 1956 was 2.5°C. lower than normal while the lower 1500 m. of the temperature profile was uniformly about 0.5°C. lower in July 1956 than in the long-term mean profile for July. Although the 1956 Phoenix temperature anomalies cited above were in different directions for January and July, they had a similar effect on the MMD for both months. Other large differences between the MMD's of columns I and II might be explained similarly but no attempt was made to do so.

From columns I and II of table 2 and the brief discussion here it is seen that mean MMD's may vary considerably from year to year. Table 2 indicates that these variations are likely to be greater during January than during July. This is attributed at least in part to the more frequent air mass changes and storm passages in January as compared to July.

Also shown in table 2 are the standard deviations, column IV, and the ranges, column V, of the daily MMD computations for January and July 1956. These data show that at most stations considerable day-to-day variation in the MMD is likely. This fact should be kept in mind throughout this report and in practical applications of mean MMD's. Compared to their corresponding averages, column III, the standard deviations in many cases are large, especially in January when at three stations the standard deviations are actually larger than the averages. This indicates that the frequency distributions are skewed. Such skewed distributions are also indicated where an average MMD occurs near one of the limits of the MMD range.

At a few stations and mostly in July the standard deviations are not large. In July the standard deviation

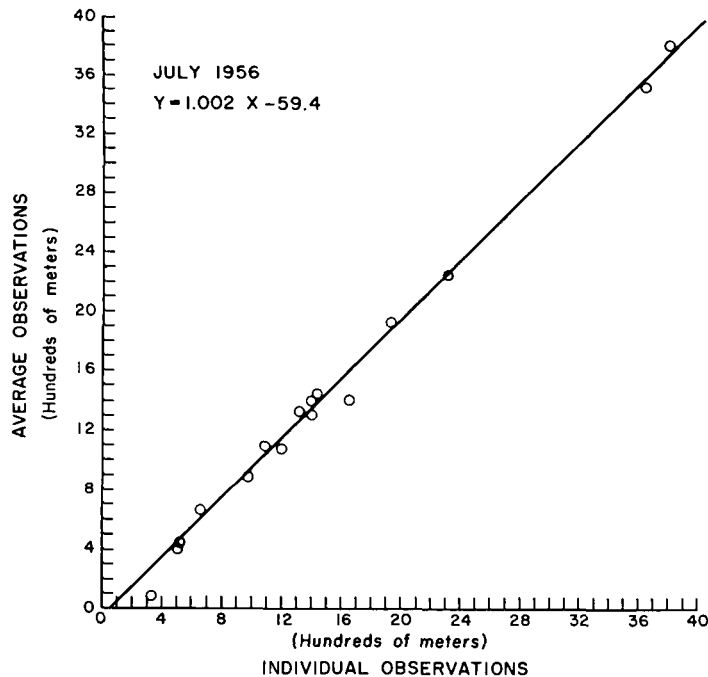


FIGURE 15.—Same as figure 14 except during July 1956.

is less than 300 m. at six stations: Brownsville, Hatteras, Miami, Oakland, Santa Maria, and Tatoosh. These are all maritime stations. At Santa Maria and Oakland the July standard deviations are only 120 and 140 m., reflecting the very persistent nature of the summer subsidence temperature inversion in that region. In January the standard deviations are barely less than 300 m. at only two stations, International Falls and Oklahoma City.

As mentioned in section 2, a dry adiabatic lapse rate was assumed in the computation of MMD's. To test this assumption the long-term mean lifting condensation levels (LCL's) with respect to corresponding MMD's were computed for January and July. As for the MMD computations, the LCL computations were based on the 10-yr. average radiosonde data and 30-yr. normal maximum surface temperatures. In addition the 10-yr. average mixing ratios in the lowest 25-mb. layer were taken as representative of moisture conditions in the lifted parcels. In January the mean LCL was not lower than the mean MMD at any of the 45 stations. The only station where this difference was close was Miami where it was 40 m.

In July over the Rockies and over the Southeastern and Gulf Coast States LCL's were less than MMD's, as sketched in figure 16. In this figure the values shown are the differences between the mean LCL's and the mean MMD's; negative values (solid isopleths) indicate that the LCL was below the MMD and positive values (dashed isopleths) indicate that the LCL was above the MMD. Over the Rockies the LCL's were below the MMD's not because the parcels were initially very moist, but mainly because the MMD's were large, which allowed

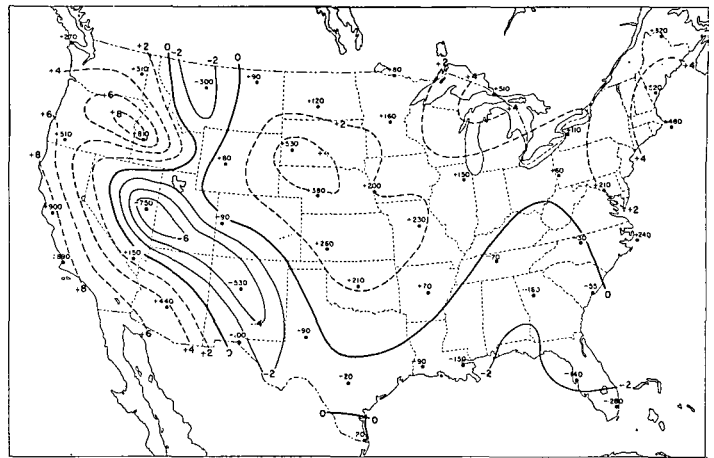


FIGURE 16.—Differences, in meters, between mean lifting condensation levels and mean maximum mixing depths during July. Negative values indicate the condensation level is less than the maximum mixing depth. Isopleths are labeled in hundreds of meters.

great adiabatic cooling of the lifted parcels. This may be seen by comparing the July mean MMD's (fig. 8) with figure 16. In the latter, negative isopleths occur over the Rockies only where MMD's are at least 2000 m., and in a large section where they exceed 3000 m. Over the Southeastern and Gulf Coast States the LCL's were slightly below the MMD's mainly because of the high moisture content of the air, which did not require great cooling to reach saturation.

At stations where the LCL's were less than the MMD's in July the LCL minus MMD differences were computed for other months. In general, the pattern shown in figure 16 (July) was quite similar to that for June and August. Over the Rockies the only negative value (LCL minus MMD) in May was at Ely and there were none over the Rockies from September through April. Over the Southeastern and Gulf Coast States LCL's less than MMD's occurred mainly during June through August, except over Florida where LCL's were less than MMD's throughout most of the year. For instance, at Miami mean LCL's exceeded mean MMD's only during January and March, and then by no more than 60 m.

The significance of an LCL being less than the MMD is that in such a case the parcel reaches saturation while it is still freely rising. As the parcel continues to rise above this level (the LCL) it then cools at the pseudo-adiabatic lapse rate, which is less than the dry adiabatic lapse rate. Since the temperature of the freely rising parcel is greater (density less) than that of the environment air at the same level, the temperature (and density) of the saturated parcel approaches that of the environment less rapidly than before it was saturated. As a consequence when the LCL is less than the MMD, as computed dry adiabatically, the parcel reaches saturation while it is still freely rising and results in a much greater MMD than

in the pure dry adiabatic assumption. As a matter of fact, because of the observed mean temperature profiles, the temperature (or density) of a freely rising saturated parcel does not reach that of its environment until the parcel reaches the base of the stratosphere, very roughly 10,000 m.

Experience indicates that extensive episodes of community air pollution are often associated with MMD's less than 1500 m. Thus, in most areas where the LCL's are less than the MMD's, the MMD's are already greater than about 1500 m. This is certainly the case over the Rockies and to a somewhat lesser degree over the Southeastern and Gulf Coast States with some exceptions over Florida. Therefore, if it is considered that for practical purposes mean MMD's greater than 1500 m. are essentially unlimited, then the assumption of a strictly dry adiabatic lapse rate in MMD computations seems permissible.

5. CONCLUSIONS AND DISCUSSION

Mean MMD's are less than 1500 m. over almost the entire contiguous United States during October through February, the main exception being over southern Florida where low LCL's result in practically unlimited MMD's. Mean MMD's are especially shallow over the United States during December and January when they exceed 800 m. at only a few stations and are less than 500 m. at many stations.

Along the middle Atlantic and New England coasts mean MMD's are relatively shallow throughout the year, and are particularly low during November through February when they are mostly less than 500 m. This is partly because of the cool Labrador current. On a yearly basis the station with the lowest mean MMD's is Nantucket, where the monthly means range between 250 and 590 m. Although mean MMD's are shallow along the middle Atlantic and New England coasts, other factors, such as relatively moderate wind speeds and frequent storm passages, tend to offset the shallow MMD's in affecting the local accumulation of air pollutants.

During March through September mean MMD's are practically unlimited over the Rockies. At the same time they are practically unlimited over Florida because of low LCL's. The other area where MMD's are affected by low LCL's is over the Southeastern and Gulf Coast States during June through August, as indicated by the areas of negative isopleths on figure 16. In other areas of the contiguous United States during March through September mean MMD's are generally less than about 1500 m. During July through September mean MMD's along the Pacific Coast are less than 500 m., which is

attributed mostly to cool coastal waters and appreciable warming aloft by subsidence. These events result in a marked temperature inversion, especially along the California coast during summer. This inversion is so strong that it extends well beyond the tops of the summer mean MMD's acting as a virtual lid even to penetrative convection.

As mentioned in section 1 of this report, an intended purpose of the computed MMD's is as a supplement to Hosler's [1] paper. In this respect it should be pointed out that Hosler tabulated the frequency of very stable atmospheric layers that occurred within 500 ft. of the surface. The mean MMD's presented in this report are the means for all days, not just those tabulated by Hosler. However, Hosler's work indicated that the stable layers, which usually began at the surface, may be expected in more than half of the nighttime observations in all seasons over almost the entire contiguous United States. Over large areas these frequencies exceeded 70 percent and over some they exceeded 90 percent. (Refer to Hosler's [1] figure 2.) Therefore, it is assumed that at night the mean extent of vertical mixing is less than approximately 1000 ft. over practically all of the United States. In some areas where Hosler's frequencies were greater than 80 percent the mean extent of vertical mixing is probably less than approximately 500 ft. It is concluded, therefore, that at night the mean extent of vertical mixing over the United States generally is severely limited. Thus, estimates of the mean maximum extent of vertical mixing during daytime are important. Where these depths are shallow the likelihood of extended periods of limited vertical mixing is large; where they are deep, such likelihood is small.

ACKNOWLEDGMENTS

Much of the work for this report was carried out while the author was stationed at the Department of Meteorology, University of California at Los Angeles. It is a pleasure to acknowledge the hospitality that was extended during that assignment. Discussions with Professor James G. Edinger of the UCLA Meteorology Department were especially helpful. Most of the mean MMD estimates were very capably carried out by Mr. Everett C. Nickerson, a meteorology student at UCLA.

REFERENCES

1. C. R. Hosler, "Low-Level Inversion Frequency in the Contiguous United States," *Monthly Weather Review*, vol. 89, No. 9, Sept. 1961, pp. 319-339.
2. Benjamin Ratner, "Upper Air Climatology of the United States," *Technical Paper No. 32, Part 1*, U.S. Weather Bureau, June 1957, 199 pp.
3. U.S. Weather Bureau, *Daily Weather Map*, Washington, D.C.

[Received March 1, 1963; revised December 16, 1963]